MICROMACHINED DERMABRADERS FOR PLASTIC SURGICAL APPLICATIONS

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ABSTRACT

Miniature abrasion tools for potential skin resurfacing applications are created using MEMS fabrication technology. The abrading microstructures are formed on silicon wafers by a one-mask bulk micromachining process based on isotropic xenon difluoride etching. The micromachined abraders (microdermabraders) are packaged and applied to human cadaveric skin to remove wrinkles. Dermabraded and intact skin regions are analyzed qualitatively and quantitatively by light microscopy and image processing techniques. Overall, the microdermabraders performed favorably compared to commercially available plastic microreplicated structures. The microdermabraders provided a consistently uniform cut through the epidermal layers of cadaveric skin, leaving little debris and minimal pitting.

INTRODUCTION

Skin resurfacing is a form of cosmetic surgery that is often used to aesthetically improve the appearance of wrinkles, skin lesions, pigmentation irregularities, keratoses, roughness, and scar revision [1-3]. There are also clinical instances where resurfacing is necessary for the removal of skin pathologies such as malignant lesions. Conventional skin resurfacing techniques using commercially available dermabraders or chemical peels may cause excessive bleeding, asymmetrical excisions, and are often time-consuming procedures that necessitate multiple sessions. Furthermore, chemical peels cannot be used for removal of large raised lesions or lesions with significant depth, and have a fairly limited patient criteria. Laserabrasion has become quite popular for skin resurfacing due to its reproducible results [4-8]. However, there is an increased risk of heat damage to the perilesional structures at the treatment site if the laser exposure time, wavelength, and tissue absorption characteristics are not simultaneously optimized [9]. Further complications include ocular injury, flammability of the laser materials, risk of reflection of the laser light that may injure those in the pathway of the reflection, and laserplumes that create a potential infectious disease risk [10]. The high cost for the use of lasers to the patient for simple skin resurfacing procedures also limits the wider application of laserabrasion.

Dermabrasion is a mechanical resurfacing technique that has been used since the early 1900's. It has been used to treat acne scars, remove raised lesions, and reduce fine lines typically associated with sun damaged skin [11]. The early days of dermabrasion were subject to many complications including increased bleeding, infections, and poor outcomes. However, advances in dermabrader technology and accrual of surgical expertise led to the subsequent acceptance of dermabrasion into routine clinical practice. Today, dermabrasion can provide a safe and inexpensive alternative to laser-based skin resurfacing procedures.

This paper is a feasibility study into the use of micromachined silicon (Si) structures as dermabrasion tools for potential skin resurfacing applications. The dermabraders are realized by bulk micromachining, packaged onto rotary bits, and tested on human cadaveric skin. The abraded skin is analyzed by image processing and histology to assess the potential of the micromachined dermabraders for plastic surgical applications.

METHODS

Experimental Overview

Micromachined Si dermabraders (microdermabraders) were compared to commercially available plastic (acrylic) microreplicated structures, some of which were coated with aluminum (Avery Denison, Mt. Prospect, IL). Study controls consisted of smooth Si and plastic surfaces. A sample size of six devices was used to evaluate the dermabrasion quality of each

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device type - microdermabraders, non-coated plastic microreplicated structures, coated microreplicated structures, smooth silicon controls, and smooth plastic controls. Each device was first examined by scanning electron microscopy (SEM) to confirm absence of defects. The device was then affixed to a rotary bit, which was mounted onto a materials testing system (MTS Alliance, MTS Corp., Eden Prairie, MN) capable of applying constant axial load to predetermined displacements. Each device was subsequently applied to cadaveric skin samples, which were frozen to simulate skin surface conditions during clinical procedures. In order to assess abrasion quality both qualitatively and quantitatively, the abraded and intact regions of the skin samples were digitally imaged using a light microscope. Surface plots and histograms were generated from these digital images to compare the performance of the different abrasion devices.

Fabrication of Dermabraders

Figure 1 presents a schematic depiction of the process flow for the fabrication of microdermabraders. The starting substrate was a 100 mm-diameter, <100>-oriented, n-type, single side polished Si wafer. First, a layer of 1200Å-thick Si_3N_4 was deposited by low-pressure chemical vapor deposition (LPCVD). This nitride layer was then patterned by standard photolithography and plasma etching processes to create a patterned masking layer for subsequent bulk micromachining of the substrate. Afterwards, the exposed Si substrate was isotropically etched using xenon difluoride (XeF_2) (XACTIX Inc., Pittsburgh, PA). Next, the residual masking layer was removed to expose the microdermabraders. Finally, the patterned silicon wafer was diced into 1 x 1 cm chips, which were then affixed to rotary bits using epoxy.

Figure 2 presents representative SEM images of two microdermabrader designs - conical and square – as well as the tetrahedral design of the commercially available plastic microreplicated structures.

Abrasion Procedure

Fresh skin from three cadavers (mean age 64±24 years) was used to evaluate the dermabraders. Prior to testing, the epidermal layers of the cadaveric skin samples were frozen using dry ice for 30 minutes. Each skin sample was fastened with clamps to the bottom platen of the materials testing system and the

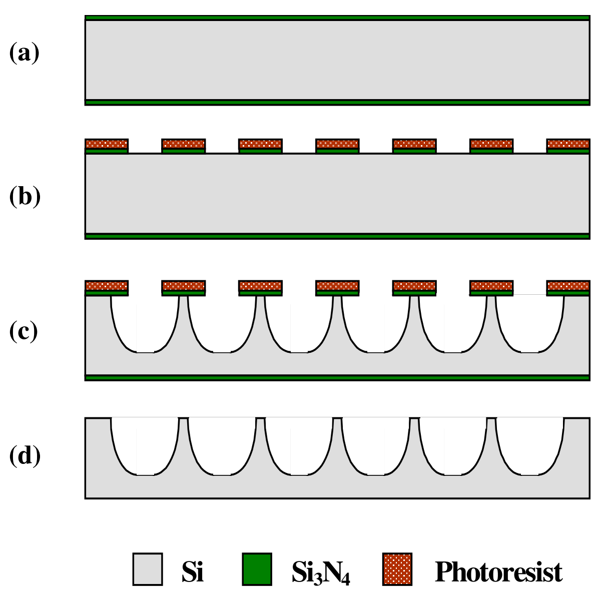

Figure 1: Fabrication of silicon dermabraders (microdermabraders) by micromachining. Cross-sectional schematics depict wafer after: (a) Deposition of 1200Å-thick layer of Si_3N_4 by LPCVD; (b) Patterning of nitride layer by photolithography and plasma etching; (c) Isotropic etching of silicon substrate using XeF_2; and (d) Removal of residual nitride and photoresist to leave behind abrading microstructures.

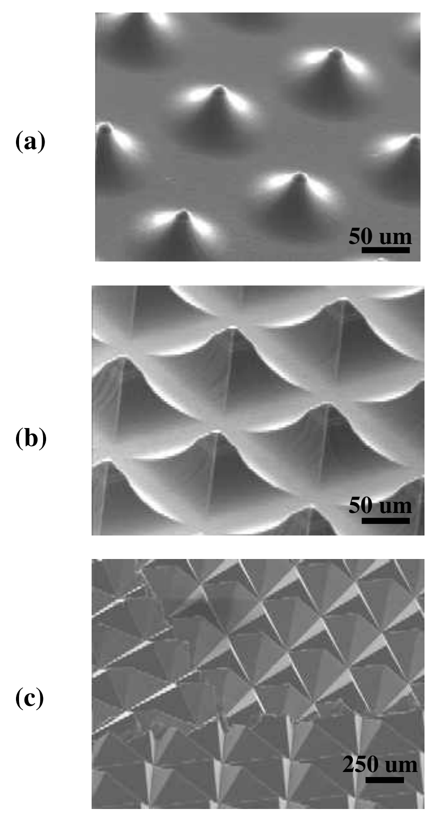

Figure 2: SEM images of different dermabrading surfaces: (a) Silicon cones; (b) Silicon pyramids; and (c) Plastic (acrylic) tetrahedra.

rotary bit was lowered onto the surface of the skin to provide an initial compressive load of 0.5-1.0 N. The rotary bit was powered to approximately 4000 rpm and the dermabrader were displaced into the skin at a rate of 0.03 mm/sec to a maximum depth of 0.25 mm. A digital image capture system (Optronics DEI 450, Optronics, Goleta, CA) was used to image both dermabraded and the neighboring intact regions of each skin sample for subsequent image analysis.

Data Evaluation

The skin samples were analyzed visually and by the image analysis software NIH Image, Scion Corp., Frederick, MD) to obtain qualitative and quantitative evaluations of dermabrasion quality. Surface plots and histograms were generated to detect differences in pixel intensities distributions between the tested and control sections of the skin. A uniform pixel intensity for the histogram data reflected a uniformly abraded surface with minimal artifacts, and hence, a narrow bandwidth. For statistical purposes, the histogram bandwidths were defined as the width between the 25% and 75% points of the entire histogram width. The mean difference was calculated as the difference of the mean bandwidths for the abraded and intact regions for each device type. Consequently, a larger mean difference would indicate a higher degree of uniformity of the abraded skin region relative to intact skin. A one-tailed students t-test was also performed on the control and abraded histogram bandwidths to investigate the possibility of statistically significant differences within a 95% confidence interval.

RESULTS

The surface plots generated from the tested and non-tested skin regions for the silicon and plastic controls did not reveal any distinct differences. However, visual inspection showed minor variations between the intact and tested regions, which were due to compression of the frozen epidermal layers during the abrasion procedure. In contrast to the controls, visual inspections and surface plots for the plastic microreplicated structures as well as the microdermabraders revealed distinct differences between tested and non-tested (abraded and intact) regions. The plastic microreplicated structures exhibited non-uniform abrading patterns, eccentric pits, and residual debris in the abraded skin regions. The microdermabraders – both conical and square designs - exhibited a cleaner, more uniform abrading pattern on the cadaveric skin compared to plastic microreplicated structures. Furthermore, the microdermabraders provided a consistently uniform

(a)

(b)

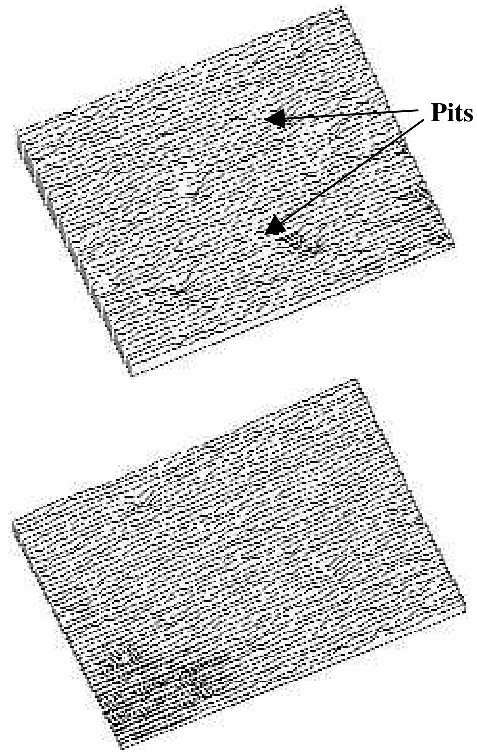

Figure 3: Surface profiles of dermabraded skin using: (a) plastic microreplicated structures, which cause eccentric pitting; and (b) microdermabraders, which exhibit minimal pitting and very smooth surfaces.

(a)

(b)

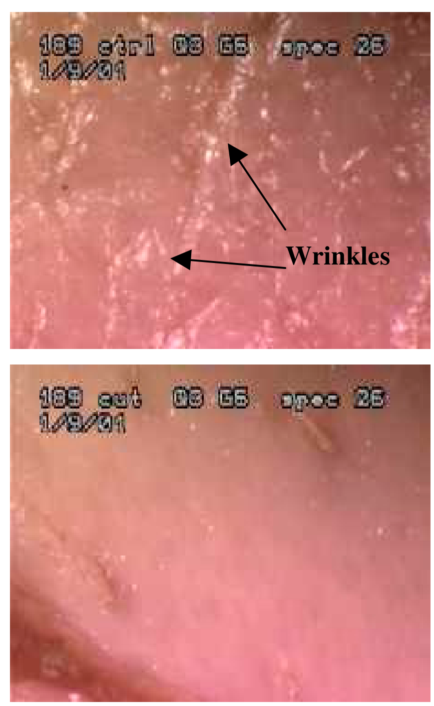

Figure 4: Photographs of cadaveric skin: (a) Before dermabrasion; and (b) After dermabrasion with silicon microdermabrader. The wrinkles and surface irregularities are eliminated by dermabrasion.

Table I: Summary of Abrasion Performance

Type of Abrader	Mean Difference (D)
Non-coated Plastic	12
Coated Plastic	19
Silicon	23

cut through the epidermal layer leaving little debris and minimal pitting.

Table I presents the mean difference (D) in histogram bandwidths. The microdermabraders exhibited the best abrasion performance (D = 23) with a strong statistically significant difference between the dermabraded and intact skin regions ($p<0.004$). The coated plastic microreplicated structures exhibited better performance (D = 19) than their non-coated counterparts (D = 12), but with weaker and comparable statistically significant differences ($p<0.05$).

CONCLUSION

The feasibility of micromachined silicon abraders for potential skin resurfacing in plastic surgical applications has been successfully demonstrated. The fabrication of the microdermabraders was realized by a one-mask bulk micromachining process based on isotropic XeF_2 etching. The performance of the microdermabraders was compared to commercially available plastic microreplicated structures through testing to remove wrinkles on human cadaveric skin. The microdermabraders provided a consistently uniform cut through the epidermal layer leaving little debris and minimal pitting compared to commercially available plastic microreplicated structures. The results of our study suggest that further development of MEMS-based tools for plastic surgical applications is justified.

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